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Design of Robust Adaptive Array Processors for Non-stationary Ocean Environments

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LONG-TERM GOALS

The overall goal of this project is to design adaptive array processing algorithms that have good transient performance, are robust to mismatch, work with low sample support, and incorporate waveguide physics in a meaningful and robust way.

OBJECTIVES

Adaptive array processing algorithms facilitate the detection and localization of quiet sources by nulling out noise and interference. These algorithms, which use the incoming data to design optimal weight vectors, provide substantial gains in performance over non-adaptive techniques. When the input is non-stationary, however, the performance of adaptive processors may be significantly degraded due to low sample support. Since ocean acoustic signals are often non-stationary due to a number of factors, *e.g.*, source motion, receiver motion, and environmental fluctuations, it is crucial to have algorithms that work in rapidly changing environments. Previous work has typically focused on the asymptotic performance of adaptive processors, and much less attention has been given to the case where the input signals change faster than the processor can reach the asymptotic limit. This project focuses on the general problem of array processing in realistic non-stationary ocean environments. It has several specific objectives: 1) To characterize the performance of existing adaptive algorithms, focusing specifically on the transient behavior and convergence rate, rather than asymptotic performance; 2) To design new adaptive algorithms that are robust and have the rapid convergence that is required in non-stationary environments; 3) To explore methods of incorporating propagation physics into adaptive processing algorithms without sacrificing robustness.

APPROACH

To develop improved array processing algorithms for non-stationary environments, this project is investigating adaptive beamforming algorithms that can operate on a single-snapshot or a very limited number of snapshots. Spectral estimation methods, such as the multitaper spectral estimator developed by Thomson [1], require only a single snapshot to produce an estimate. This project is exploring how to adapt the multitaper approach to the spatial spectral estimation problem.

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The signal processing algorithms developed in this project are being tested on both simulated and experimental data. The primary focus in this project was on analyzing data from the ONR-sponsored SPICE04/LOAPEX experiment. The SPICE04 data set consists of measurements from two vertical line arrays deployed in the North Pacific. In 2007-2008 horizontal line array data from SWellEx-96, another ONR-sponsored experiment, was also analyzed using the multitaper method.

In addition to the principal investigator (PI) Kathleen Wage, three master's students at George Mason University worked on this project. Songshun Xu researched previous work on single-snapshot adaptive array processing algorithms, and summarized in a "scholarly paper" (a type of a master's project at GMU) presented in summer 2008. Khalid AlMuhanna explored the problem of using ambient noise measurements, specifically the sample covariance matrix, to estimate the mode shapes for a deep water waveguide. Mr. AlMuhanna defended his master's thesis in June 2008. Richard Wheelock applied multitaper methods to analyze the angular spread of signals received on horizontal arrays deployed in the SWellEx-96 experiment. Mr. Wheelock defended his MS thesis in August 2008.

WORK COMPLETED

SPICE04/LOAPEX Analysis: An initial analysis of the 250 Hz receptions on the 40-element shallow VLA deployed for SPICE04 was completed. Results of this analysis were presented at North Pacific Acoustic Laboratory (NPAL) Workshop in April 2006 [2] and at the fall 2006 Meeting of the Acoustical Society of America [3]. In 2008 Kathleen Wage and PhD student Tarun Chandrayadula developed a method of estimating missing array navigation data using an empirical orthogonal function model of the array motion. Mr. Chandrayadula presented this work at the IEEE/MTS Oceans Conference in September 2008 [4]. The method has been applied to estimate missing navigation data for the LOAPEX experiment, facilitating processing of the acoustic receptions.

Multitaper Array Processing: An important focus of this project is an investigation of the application of multitaper spectral estimation methods to the passive sonar array processing problem. The initial work on this topic was summarized in an invited talk given at the Acoustical Society of America meeting in June 2007 [5] and an invited paper presented at the Asilomar Conference on Signals, Systems, and Computers in November 2007 [6]. While the initial work focused on applying the multitaper approach to equally-spaced arrays, this year's work investigated how to apply the method to non-uniform arrays, such as the horizontal array deployed in the SWellEx-96 experiment. Master's student Richard Wheelock used the multitaper processor designed for the SWellEx array to analyze multipath spread in the SWellEx data set. Experimental results were compared to ray-based simulations.

Deep Water Ambient Noise Analysis: The year-long deployment of long VLA's as a part of the SPICE04 experiment provided an opportunity to study ambient noise statistics in the deep water channel. This project analyzed the deep water noise in the North Pacific, focusing primarily on whether an eigenanalysis of noise covariance matrices revealed anything about the underlying acoustic modes. Results indicate that the eigenvectors of the noise covariance matrix resemble the low-order acoustic modes. Master's student Khalid AlMuhanna presented the initial results of this work at the the IEEE Underwater Acoustic Signal Processing Workshop in October 2007 [7], and PI Kathleen Wage presented the latest results at the summer 2008 meeting of the Acoustical Society of America [8].

Planning for 2009 Philippine Sea Experiment: In 2008 Kathleen Wage analyzed the effect of array

element spacing on mode resolution for the Philippine Sea environment. This work led to a proposed design for the axial segment of the distributed vertical line array that will be deployed in the 2009 Engineering Test/Pilot study.

RESULTS

This section summarizes results on the SPICE04 analysis, multitaper array processing, and deep water noise analysis obtained during the life of the grant.

SPICE04 Analysis: During the SPICE04 experiment a 40-element vertical line array (VLA) received signals from two broadband sources at ranges of 500 km and 1000 km. Both sources were moored at depths near the sound channel axis, thus they directly excited the lowest modes. The VLA was designed to spatially resolve 20 modes at the center frequency of 250 Hz. Figure 1(a) shows the modeshapes for the environment at the SPICE VLA location assuming a frequency of 250 Hz. The line of crosses indicates the locations of the sensors for the 40-element shallow VLA deployed in SPICE04. Blue crosses mark the good sensors and red crosses mark the locations of the two bad sensors. To illustrate the mode-resolving power of the SPICE VLA, Figure 1(b) shows the mode filter “beampattern”. Narrowband mode filters are commonly designed using a least squares criteria, which leads to the pseudo-inverse (PI) mode filter. For the PI filter the vector $\hat{\mathbf{a}}(\omega)$ of estimated mode coefficients at frequency ω is computed as follows

$$\hat{\mathbf{a}}(\omega) = \underbrace{(\mathbf{E}^T \mathbf{E})^{-1} \mathbf{E}^T}_{\mathbf{W}^T} \mathbf{p}(\omega), \quad (1)$$

where $\mathbf{E}(\omega)$ is the matrix of modeshapes sampled by the array and $\mathbf{p}(\omega)$ is the measured pressure along the array. The mode filter is denoted by the matrix \mathbf{W} . In mode filtering, the beampattern is defined as $20 \log_{10}(\mathbf{W}^T \mathbf{E})$. The m th row of the beampattern matrix corresponds to the projection of the modes into the estimate for mode m . The PI filter is constrained pass the desired mode with unity gain and place nulls at the location of other modes included in the pseudo-inverse. It does not constrain the output at modes not included in the pseudo-inverse [9]. The beampattern in Figure 1(b) is for a 20-mode processor, thus the beampattern shows a diagonal structure up to mode 20. As indicated by the figure, modes higher than 20 are expected to project into the lower order mode estimates. Assuming the pseudo-inverse is well-conditioned, this modal crosstalk is relatively low.

Broadband mode filtering was implemented for the SPICE04 data by first transforming the data, implementing narrowband PI mode filters for each frequency bin, and then inverse transforming. Corrections for VLA motion are implemented as a part of the mode filtering process. See the papers by Wage *et al.* for more information about mode filtering methods [9, 10]. Figure 2 shows an example of the received signals at the VLA from each of the two sources and the corresponding estimated time series for modes 1, 5, and 10. The received pressure field consists of a set of early arrivals that look like up- and down-going planewaves followed by a complex finalé consisting of the low order modes. As expected, the reception due to the source at 1000 km range shows more dispersive spreading than the source at 500 km range. The finalé also appears to be more complex at 1000 km range due to additional internal wave scattering. The mode estimates shown in Figure 2 reveal several important characteristics. First, the crosstalk from the higher order modes that make up the planewave arrivals is obvious in each of the plots. This crosstalk could be removed by time-windowing since it is well-separated in time from the true low-mode arrivals in the finalé. Second, at the shorter (500 km) range, the lowest modes are

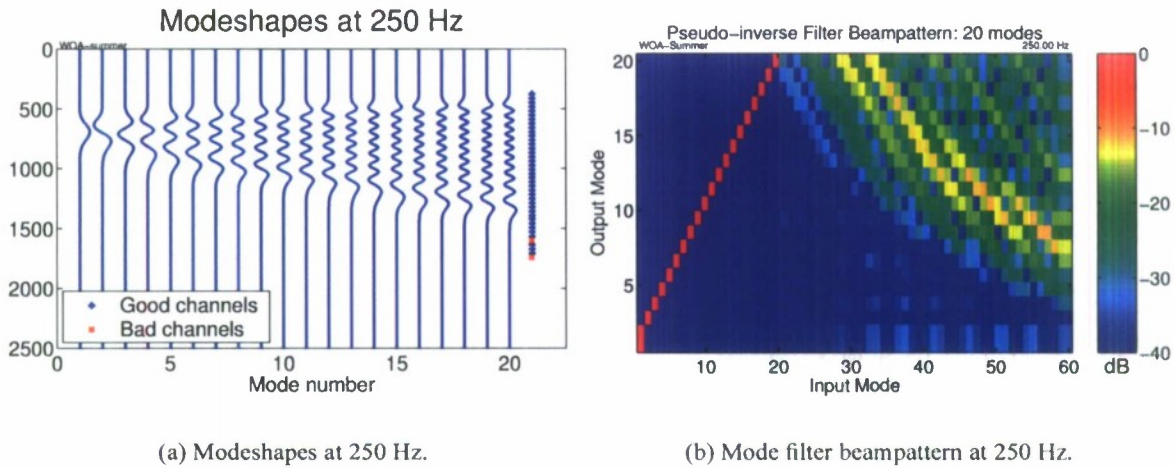


Figure 1: Modeshapes and the corresponding mode filter beampattern at the SPICE04 VLA location. The line of blue crosses in Figure 1(a) indicates the good sensor positions; the red crosses indicate sensor failures. The mode filter beampattern in Figure 1(b) was computed assuming a pseudo-inverse mode filter designed for 20 modes. For more information on mode filter beampatterns, see [9].

dominated by a single arrival. At the longer (1000 km) range, there is more evidence of multipath spread within each mode. This is to be expected since the longer range should be more affected by internal wave scattering. Figure 3 shows the stacked time series for mode 1 over a 50-day period of the experiment. There is some obvious time drift in the estimates that can probably be attributed to motion of the sources. (Source motion was measured and will be removed in future analysis.) Figure 3 indicates that mode 1 exhibits a relatively sharp cutoff after the dominant arrival comes in. Note that this is in contrast to data from the earlier ATOC experiment, where the main arrival was followed by a series of lower amplitude arrivals [10]. These weak late arrivals were attributed to bathymetric scattering near the ATOC source located on Pioneer Seamount. Assuming that bathymetric scattering is responsible, we would not expect to see these weak late arrivals when the source is suspended in the water column, as the SPICE04 sources were. The absence of these late arrivals simplifies the analysis of the SPICE04 data set, making it easier to determine the fluctuations due to internal waves.

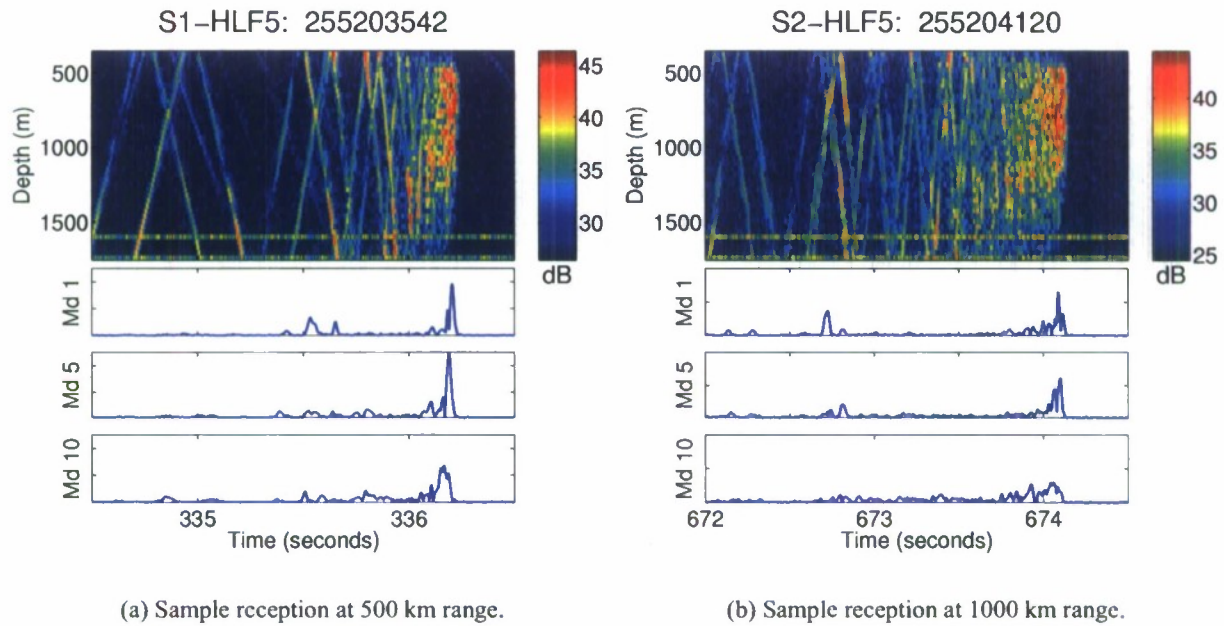
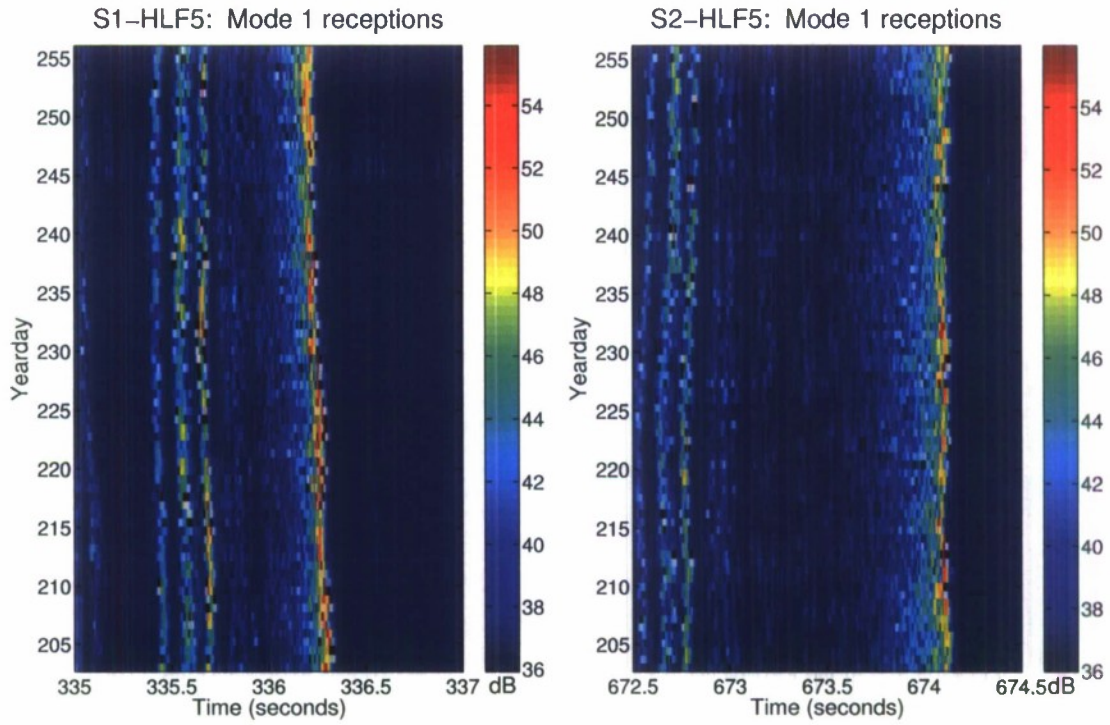


Figure 2: Receptions at the shallow VLA from the sources S1 and S2 during the SPICE04 experiment. The top plots in each column show the received pressure as a function of time and depth. The early arrivals consist of planewaves and the late-arriving energy consists of the lowest order modes. As expected the receptions at 1000 km range show more dispersive spreading than the receptions at 500 km range. The lower three plots in each column show the estimated time series for modes 1, 5, and 10. Note the presence of crosstalk from the early planewave arrivals into the modes.



(a) Mode 1 arrivals at 500 km range.

(b) Mode 1 arrivals at 1000 km range.

Figure 3: Comparison of the estimated time series for mode 1 for the S1 (Figure 3(a)) and S2 (Figure 3(b)) sources in the SPICE04 experiment. The plots show the receptions over 50 days of the experiment. Note that source motion has not been removed from these plots, thus there is a noticeable drift of the arrival times, particularly for source S1 at 500 km range.

Multitaper Array Processing: The multitaper method, formulated by Thomson for nonparametric spectral estimation [1], is widely used in the analysis of geophysical time series, but only a few researchers have applied it to the spatial spectral estimation problem, *e.g.*, [11, 12, 13]. The basic idea is to apply a set of orthonormal tapers (windows) to the data and then average the spectra obtained with these windows. Averaging over different tapers reduces the variance of the spectral estimate, in the same way that averaging over snapshots in the conventional Welch-Bartlett approach [14] reduces the variance.

Figure 4 illustrates a basic framework for multitaper array processing. As shown, multitaper processing can be viewed as a series of operations. First, the data is passed through a beamspace processor that projects the data into several orthogonal beams centered around the angle of interest θ . The beamspace is defined by a set of orthogonal tapers such as the discrete prolate spheroidal sequence (DPSS) tapers suggested by Thomson. As an example, Figure 5 shows the beam response of a set of four DPSS tapers. To compute an estimate of the continuous spectrum, the outputs of the beamspace processor are averaged, *i.e.*, the multitaper estimate is

$$S_{MT}(\theta) = \sum_{k=1}^K \alpha_k |q_k(\theta)|^2, \quad (2)$$

where α_k is the weight given to the k beam output. The weights can be set to $\frac{1}{K}$ for a simple average or determined adaptively (see Thomson's seminal paper [1] for additional details). Equation 2 provides an estimate of the continuous spectrum, but as Thomson suggests, line components need to be estimated separately. In the passive sonar problem, line components correspond to planewave arrivals. These can be estimated using a linear regression on the output of the beamspace processor. Drosopoulos and Haykin discuss the detection of line components in detail for a radar problem [11]. To work with sonar data, where the signal is typically modeled as complex Gaussian, these techniques must be modified slightly, as discussed in [6]. An iterative scheme is useful for detecting low-level planewave components in the presence of loud interferers. After one pass through the beamspace processor, the planewave signals are estimated and removed. The residual signal is passed through the beamspace processor again, and the planewave detection/estimation algorithm is repeated. Figure 6 illustrates the output of the multitaper processor after each iteration when the input signal consists of two closely-spaced planewaves. For this simulation the array had 128 elements with half-wavelength spacing. The two sources had different power levels: the first had 20 dB signal-to-noise ratio (SNR) with respect to a white noise floor and the second had -10 dB SNR with respect to the noise floor. As Figure 6 shows, when no planewave detection is implemented, the sources appear as a blurred peak in the output spectrum. After the first iteration, the strong source is detected, but the weak source still appears to be blurred. After the second iteration, both the strong and weak sources are clearly visible in the output.

Figure 7 compares the performance of the multitaper processor with the performance of the standard minimum power distortionless response (MPDR) processor for a complex scenario. (See the text by Van Trees for a thorough description of the MPDR method [15].) In this example, the array consists of 128 elements with half-wavelength spacing. The environment contains one moving source and 13 stationary interferers. The moving source has a -10 dB SNR with respect to the white noise floor; the stationary interferers have varying power levels. Note that the interferers located near endfire (four near forward endfire and four near aft endfire) are perfectly coherent. Each processor uses 4 snapshots to compute its estimates; the MPDR processor requires diagonal loading to stabilize the inversion of its

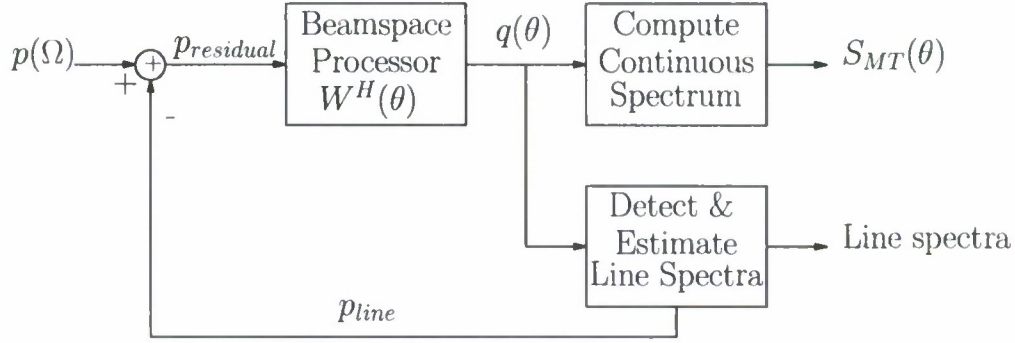


Figure 4: Multitaper processing framework. The multitaper approach projects the data into an orthogonal beamspace and computes the spectral estimate by averaging over the beam outputs. An iterative algorithm is used to remove planewave (line) components.

sample covariance matrix. Figure 7 shows that the multitaper processor produces spatial spectra with significantly lower variance than the MPDR processor. As a result the low-level moving source is easier to see in the multitaper output than it is in the MPDR output. In addition, the multitaper processor handles the coherent sources without a problem, whereas the MPDR processor nulls out some of the coherent signal components. While forward-backward averaging can help the MPDR processor with coherent sources, this requires additional computation that the multitaper approach does not require. As Figure 7 illustrates, the multitaper processor performs extremely well for a long array with very low numbers of snapshots. Additional work is ongoing to quantify the performance of the multitaper processor and to adapt the multitaper method to process non-planewave signals.

In 2006-2007 we showed that the multitaper approach works well with low numbers of snapshots, and can reliably detect low-level planewave arrivals in a complicated background containing coherent and incoherent interference sources [6]. The main accomplishment in 2007-2008 was applying the multitaper method to analyze real horizontal line array data from the ONR-sponsored SWellEx-96 experiment [16]. Since SWellEx used unequally-spaced arrays, new taper designs had to be implemented. In Thomson's original derivation, the sample rate is assumed to be uniform, and the resulting tapers correspond to the discrete prolate spheroidal sequences (DPSS). Bronez extended Thomson's spectral estimation method to irregularly sampled multidimensional processes by deriving a set of generalized prolate spheroidal sequences (GPSS) [17, 18]. The derivation of the GPSS is summarized as follows. The goal in multitaper approach is to estimate the integrated spatial spectrum, i.e.,

$$P_A = \frac{1}{2\pi} \int_{A_{\min}}^{A_{\max}} S(k_z) dk_z,$$

where the analysis band A determines the spatial resolution of the estimator. Bronez focused on quadratic estimates of the power spectrum, i.e.,

$$\hat{P}_A = \sum_{k=1}^K |\mathbf{w}_k^H \mathbf{p}|^2 = \mathbf{p}^H \mathbf{W} \mathbf{W}^H \mathbf{p} \quad (\mathbf{p} = \text{received data vector}).$$

Bronez determines an optimal set of tapers that 1) guarantee an unbiased estimate when the spatial spectrum $S(k_z)$ is flat across the band, 2) minimize the variance of the spectral estimator, and 3)

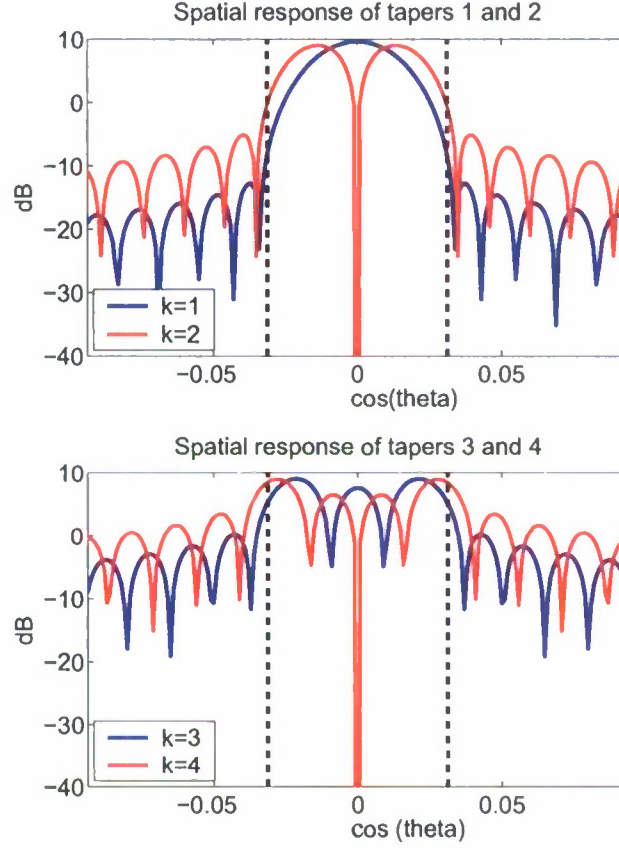


Figure 5: Beam response of four discrete prolate spheroidal sequence tapers used in a typical multitaper spatial processor.

minimize amount of “global” bias (due to signals outside analysis band). Using these criteria, the resulting optimization problem can be written:

$$\text{Min} \left(\sum_{k=1}^K \mathbf{w}_k^H \mathbf{R}_B \mathbf{w}_k - \sum_{k=1}^K \mathbf{w}_k^H \mathbf{R}_A \mathbf{w}_k \right) \quad \text{s.t.} \quad \sum_{k=1}^K \mathbf{w}_k^H \mathbf{R}_B \mathbf{w}_k = \frac{(A_{\max} - A_{\min})}{2\pi}.$$

Then the GPSS tapers are a solution to the following generalized eigenvalue problem:

$$\mathbf{R}_A \mathbf{w}_k = \lambda_k \mathbf{R}_B \mathbf{w}_k.$$

where

$$\mathbf{R}_A(n, m) = \frac{1}{2\pi} \int_A e^{-jk_z(z_n - z_m)} dk_z \quad \mathbf{R}_B(n, m) = \frac{1}{2\pi} \int_B e^{-jk_z(z_n - z_m)} dk_z$$

B represents the signal band, i.e., the band over which signals could be arriving. For equally-spaced arrays, $\mathbf{R}_B \sim \mathbf{I}$, yielding a standard eigenvalue problem and the DPSS tapers. If K of these GPSS tapers are used in the spectral estimate, the resulting bias and variance of the estimate are given below:

$$\text{Bias} \sim \frac{(A_{\max} - A_{\min})}{2\pi K} \sum_{k=1}^K (1 - \lambda_k) \quad \text{Var} \sim \frac{1}{K} \left| \frac{(A_{\max} - A_{\min})}{2\pi} \right|^2$$

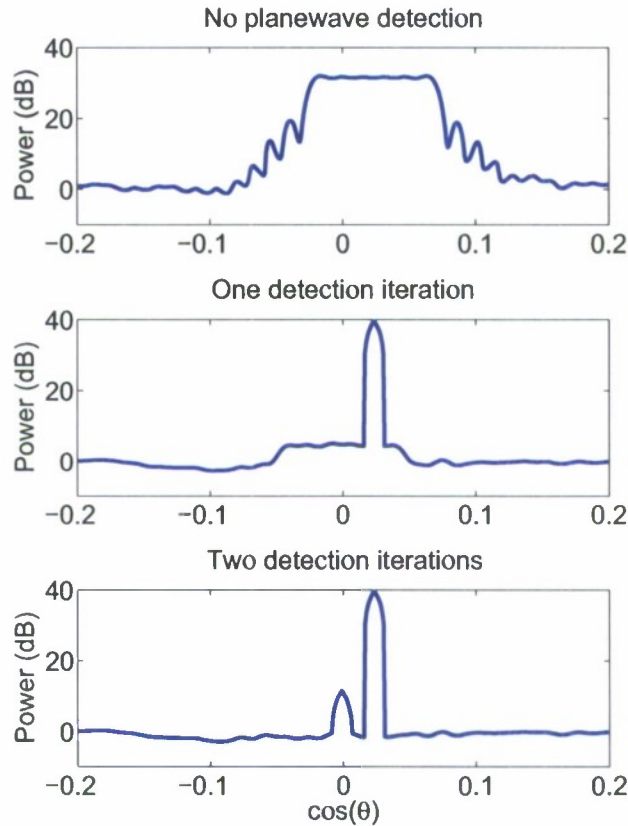


Figure 6: Example of iterative detection of planewave components. The plots show results for a 128-element array with half-wavelength spacing. Two planewaves with SNR's of 20 dB and -10 dB relative to a white noise floor are impinging on the array. With no planewave detection, the output spectrum is the blurred peak shown in the top plot. The results of the first detection iteration (shown in the middle plot) indicate that the strong planewave is detected. After the second detection iteration (bottom plot), both planewaves are visible.

Figures 8 and 9 illustrate the application of the GPSS design method to the 28-element unequally-spaced horizontal line array (HLA) used in SWellEx-96. The left plot of Figure 8 shows the generalized eigenvalues as a function of the resolution bandwidth, and the right plot shows the corresponding sidelobe leakage. The plots show the results for the first 6 GPSS tapers. As indicated above, the bias (or leakage from outside the analysis band) goes down as the eigenvalue λ_k increases, thus the tapers that should be used are the ones whose eigenvalues are close to 1. For the SWellEx array operating at 200 Hz, two good tapers will be obtained if the resolution half-bandwidth is chosen to be $u = 0.3$ (u is the directional cosine). Figure 9 shows these two tapers and their corresponding beampatterns. Note that the two tapers are essentially non-zero over different parts of the array, thus the GPSS solution suggests that sub-array processing provides the best sidelobe performance for this array. Figures 10 and 11 illustrate the good performance (as compared to conventional and minimum variance adaptive processing) of the multitaper method on real data from SWellEx-96.

Deep Water Ambient Noise Analysis: This project investigated the idea of estimating the acoustic

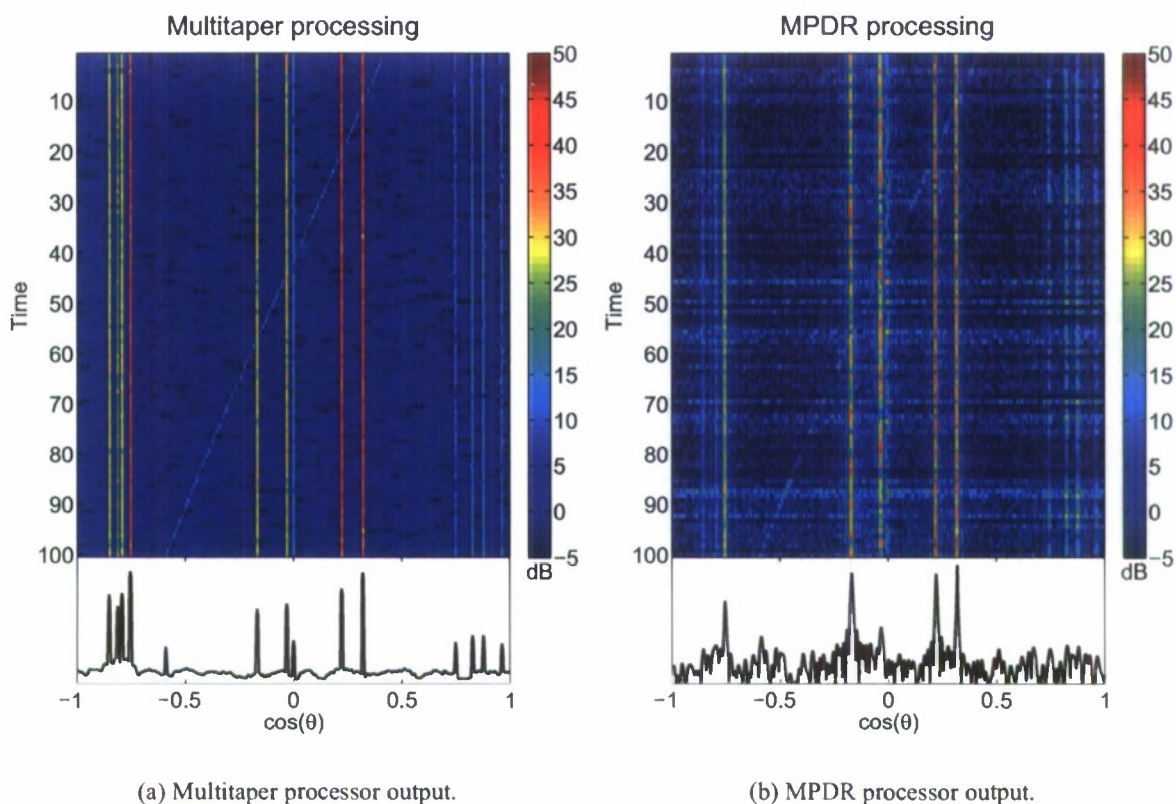


Figure 7: Comparison of the outputs of the multitaper and minimum power distortionless response processors for a complex scenario containing one moving source and 13 stationary interferers. The array consists of 128 elements with half-wavelength spacing. The color images show the estimated spatial spectra for 100 different trials, and the line plots at the bottom of each figure show the results for the 100th trial.

modeshapes using deep water ambient noise measurements made during the SPICE04 experiment. Although noise measurements were not the primary focus of SPICE04, the experiment provided a large data set of measurements in the band below 200 Hz made with a 40-element vertical line array (VLA). The basic idea is that ambient noise can be represented as a sum of uncorrelated acoustic modes, which is a reasonable assumption for distant sources, e.g., see the work of Kuperman and Ingenito on noise modeling [19]. In this case the eigenvectors of the noise covariance matrix for a vertical line array should correspond to the sampled modes. Other authors have investigated using an eigendecomposition of the noise covariance to estimate the mode functions in shallow water, e.g., Wolf et al. [20], Hursky et al. [21], and Nielsen and Westwood [22]. While the same approach should work for deep water environments, very few deep water experiments have deployed arrays with sufficient aperture to resolve the modes. The work of D'Spain et al. on estimating acoustic modes using measurements of earthquake T-phase arrivals is the only deep water example of this method we have found in the literature.

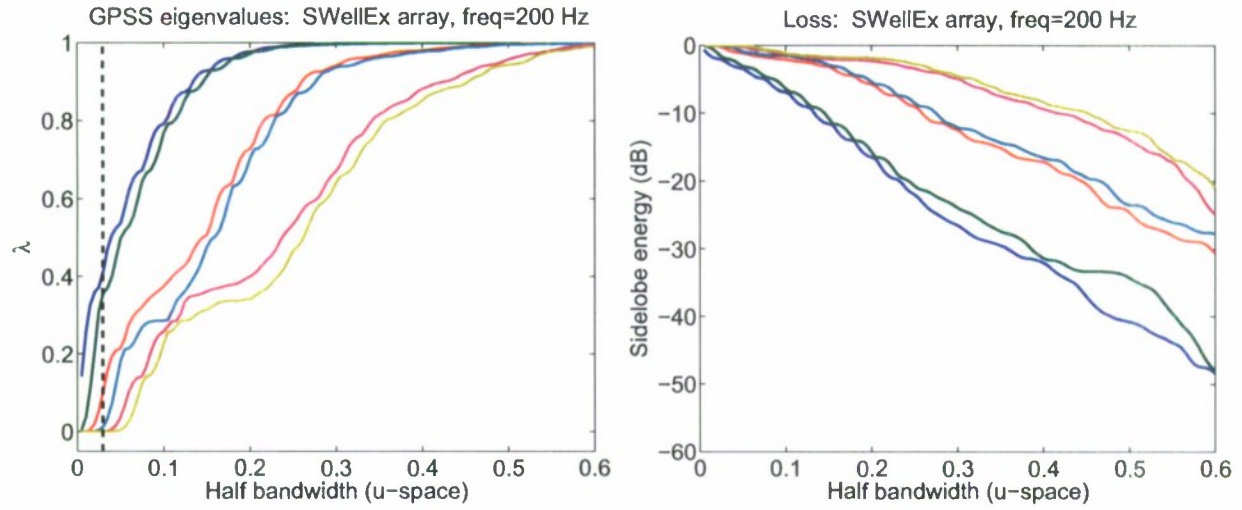


Figure 8: Generalized prolate spheroidal sequences for SWellEx-96. The left plot shows the generalized eigenvalues as a function of the resolution bandwidth for the 28-element SWellEx-96 geometry operating at a frequency of 200 Hz. The right plot shows the corresponding sidelobe leakage ($1 - \lambda_k$) for each taper. The dashed line in the left plot indicates the resolution of an untapered conventional beamformer.

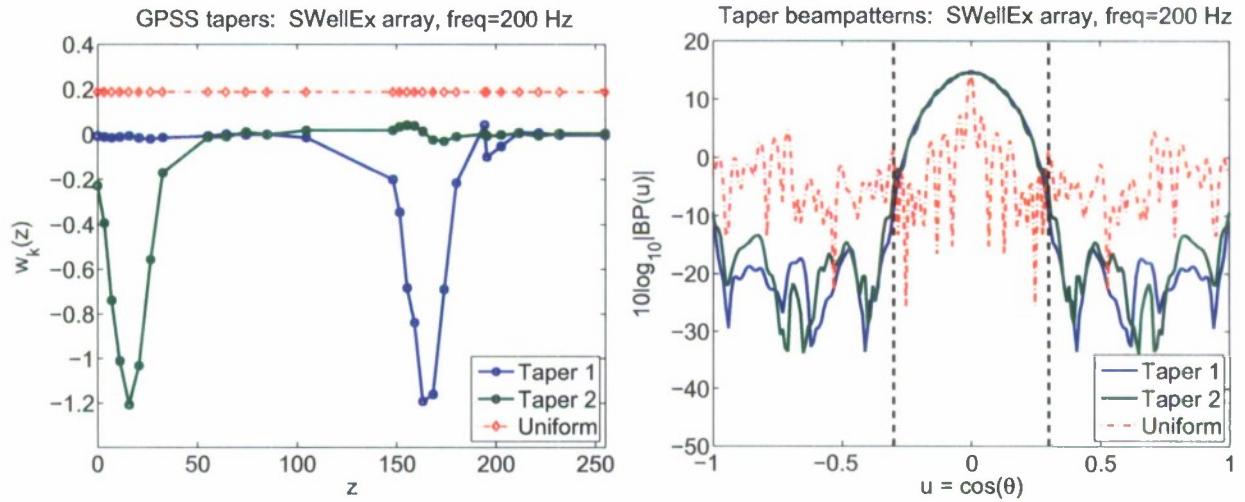


Figure 9: Generalized prolate spheroidal sequence (GPSS) tapers and their corresponding beampatterns. The left plot shows the first two GPSS tapers designed for the SWellEx-96 array operating at 200 Hz. The right plot compares the beampatterns for these tapers with the pattern for the conventional (uniformly-weighted) beamformer. The sidelobe performance of the GPSS tapers is significantly better than for the uniform weighting, at the expense of reduced resolution.

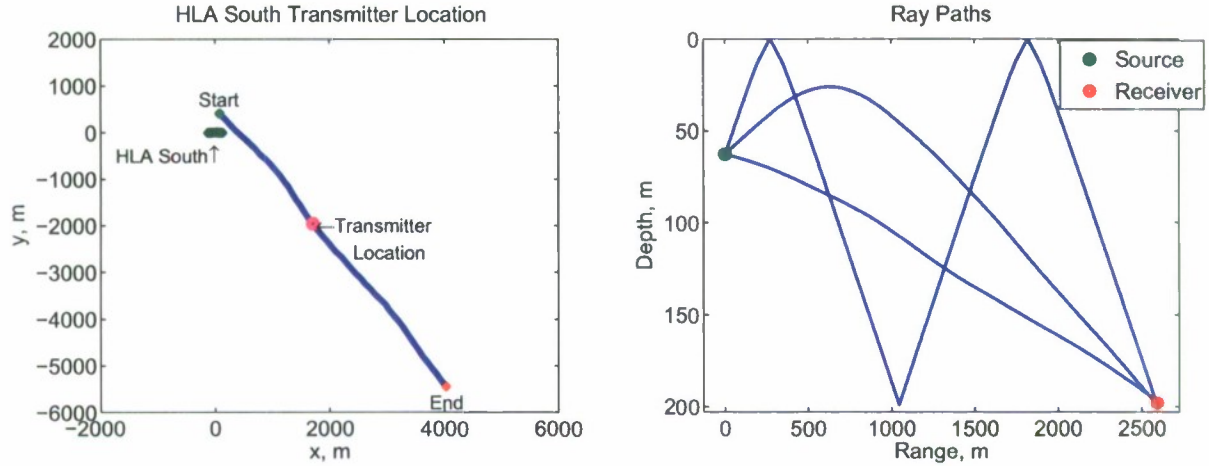


Figure 10: *SWellEx-96 experimental setup and ray theory predictions. The left plot shows the location of the transmitter and the South horizontal receiving array. For this case the range is 2.6 km. The right plot shows the ray theory predictions for propagation from the source at a depth of approximately 60 m to the bottom-mounted receiving array. Ray theory predicts three arrivals: two refracted paths and one reflected path.*

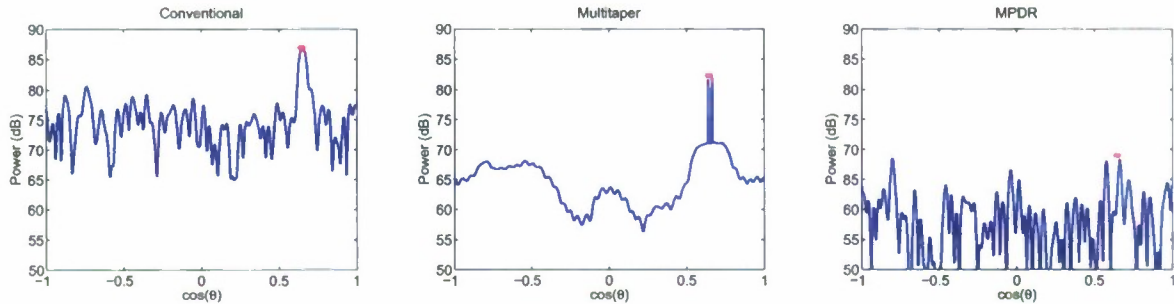


Figure 11: *Comparison of beamformer performance for the SWellEx-96 reception at a range of 2.6 km. The three plots show the results of conventional beamforming, multitaper beamforming, and minimum power distortionless response (MPDR) beamforming [15]. Each beamformer had access to 4 snapshots of data; the MPDR beamformer was diagonally-loaded to stabilize the inverse. The x's on each plot mark the arrival angles predicted by ray theory. While the conventional beamformer is unable to resolve the multipath and the MPDR output is unreliable, the multitaper processor successfully localizes two of the three predicted arrivals.*

This project focused on the important signal processing issues involved in this type of mode inversion. The work described in [23] explored the effects of analysis frequency, array aperture, array tilt, and number of data snapshots using a set of simulations designed to model the SPICE04 environment. The conclusions of the simulation study are as follows. First, as expected, the aperture of the array determines which acoustic modes can be extracted from the eigendecomposition of the noise covariance. The longer the aperture, the more modes can be successfully extracted. Second, the analysis frequency also affects which modes can be estimated in this manner. As frequency increases, the number of propagating modes increases. If the number of propagating modes exceeds the number of hydrophones on the array, then the results are ambiguous. Also the frequency affects the turning depths of the modes. As frequency decreases, the turning depths get farther apart, thus requiring arrays with greater aperture in order to span the modes. Third, tilt can have a significant effect on the modeshape estimates. While the array location can be tracked using a transponder network, it is difficult to use the navigation information to correct for tilt because the direction of the noise signals is unknown (in general noise is coming from all directions). Fourth, the number of snapshots determines the accuracy of the noise covariance matrix estimate, thus the accuracy of the eigenvectors of that matrix. For the SPICE04 array geometry, the simulation study indicates that it is possible to reliably estimate the lowest two modes for frequencies on the order of 10-20 Hz. The SPICE04 VLA spanned 1400 m of a 5500 m deep waveguide. With this span, tilts up to 1 degree across the array have no effect on the mode estimates. The simulations showed that $100N$ snapshots (where N = number of hydrophones) is sufficient to produce a good estimate of the eigenstructure of the noise. The SPICE04 noise recordings contain enough data that acquiring $100N$ snapshots for the analysis is not a problem.

In addition to simulation studies, this project applied the empirical mode analysis technique to real data from the SPICE04 experiment. As an example, Figure 12 compares the empirical modes determined by eigendecomposition with the true modes of the waveguide for yearday 455 of the experiment. The true modes were determined by the standard Prufert mode code using the sound speed profile obtained from temperature and salinity measurements made along the VLA. As expected, the agreement for modes 1 and 2 at the 11 Hz center frequency is quite good. Figure 12 also shows the correlation between the empirical modeshapes and the true modeshapes, which is a useful indicator of how closely the estimates agree. Figure 13 shows the empirical modeshapes as a function of frequency for the first two acoustic modes on yearday 455. These plots demonstrate that good performance is achieved for frequencies less than 20 Hz. The results for many other yeardays are similar, though the method is not successful for all yeardays. Based on the analysis of the SPICE04 data set, the eigendecomposition approach has difficulties on days when the noise level is exceptionally high at low frequencies. These high noise events appear to correlate with high wind stress (as measured by satellite), which could indicate the presence of a storm above the array. If there is a local storm, the assumption of distant noise sources would be violated, causing the method to fail. Further analysis of the high noise cases is ongoing.

IMPACT/APPLICATIONS

The Navy has a vital interest in being able to detect and localize quiet sources in the presence of high levels of ambient noise and strong moving interferers, such as surface ships. The expected outcomes of this research are new algorithms for processing non-stationary signals and new approaches for incorporating propagation physics into these algorithms. As the SWellEx-96 analysis described in this report demonstrates, the multitaper approach is useful for analyzing multipath arrivals on horizontal line arrays. In addition, the SPICE04 noise analysis suggests that analyzing noise data can provide valuable

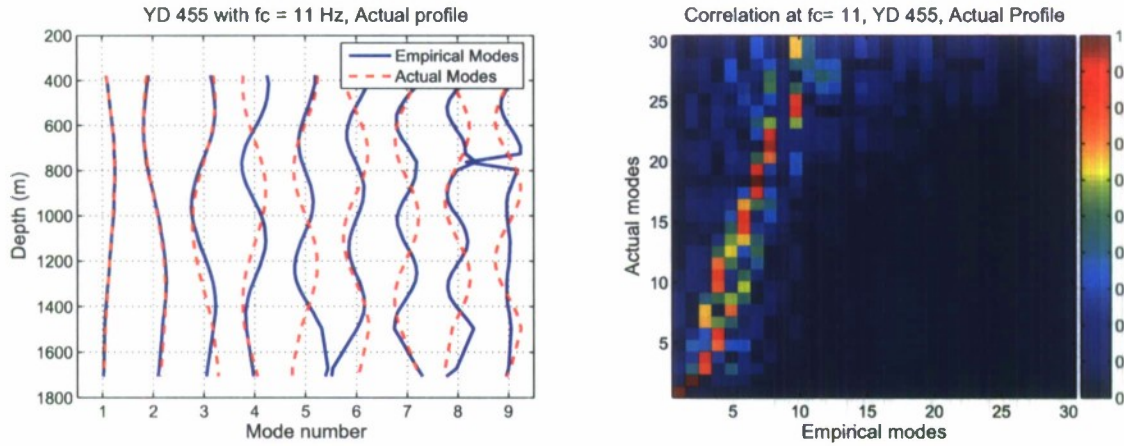


Figure 12: Comparison of empirical modes computed from an eigenvector decomposition of the noise sample covariance matrix with the modes computed using the Prufer mode code [24] and the measured environmental profile. The left plot shows the modeshapes, and the right plot shows the correlation of the empirical modes with the actual modes. These plots show the results for a center frequency of 11 Hz. At this frequency the first two empirical modes show excellent agreement with the true modes of the waveguide.

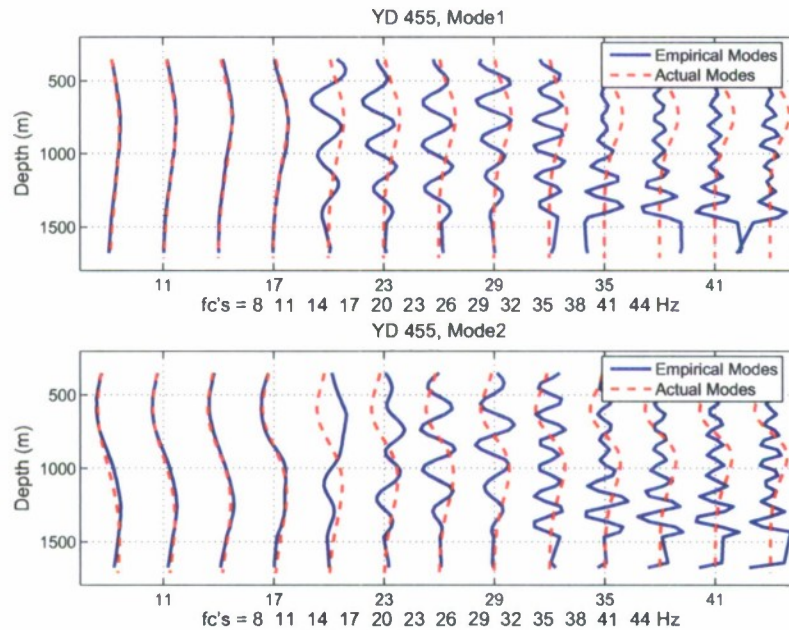


Figure 13: Empirical modeshapes for modes 1 and 2 as a function of frequency (solid lines). The empirical modes were derived from an eigendecomposition of a noise covariance matrix measured on yearday 455 during the SPICE04 experiment. For reference the plots also show the actual modes computed by the Prufer code [24] for the measured sound speed profile (dashed lines). Agreement between the empirical modes and the true modes is good for frequencies less than 20 Hz.

information about the deep water waveguides, *i.e.*, a measurement of the modeshapes. This project is exploring whether similar measurements can be used to estimate the sound speed profile. The ability to determine sound speed or other characteristics of the channel without having to measure them directly is relevant to the design and development of adaptive sonar systems. This project also has relevance for science-related applications. Specifically, the adaptive algorithms developed in this research is being used to analyze data from long-range propagation experiments sponsored by ONR. The results will provide useful data for studies of propagation physics and tomographic inversions.

RELATED PROJECTS

This project is closely related to the Navy STTR N04-T011 Phase II award that is a joint project between 3 Phoenix, LLC and Dr. Kathleen Wage. The 3 Phoenix PI's are Dr. Russ Jeffers and Mr. Bruce Gallemore. The STTR award funded the first part of Richard Wheelock's master's work. In addition, this project is closely related to ONR Award N00014-06-1-0223, which is an Ocean Acoustics Graduate Traineeship grant for Tarun Chandrayadula, one of Dr. Wage's Ph.D. students. Mr. Chandrayadula is investigating statistical models for low-frequency acoustic signals propagating underwater and designing signal processing techniques to mitigate fluctuations due to internal waves. In addition to the collaboration with Mr. Chandrayadula, the PI also has collaborations with members of the ONR-funded North Pacific Acoustic Laboratory (NPAL) group. The NPAL PI's are Dr. Peter Worcester (Scripps) and Dr. James Mercer (APL-UW). Dr. Wage attends the yearly NPAL workshops and went to sea on the deployment and recovery cruises for the 2004-2005 experiment. She is using data collected during this experiment to test new adaptive processing algorithms. Dr. Wage is also participating in planning for the upcoming experiment in the Philippine Sea, scheduled for 2009.

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PUBLICATIONS

K. E. Wage, "Multitaper array processing," *Proceedings of the 41st Asilomar Conference on Signals, Systems, and Computers*, pp. 1242-1246, November 2007. [published, invited]

Khalid AlMuhanna, *Acoustic Modeshape Inversion Using Deep Water Ambient Noise Measurements*, Master's thesis, George Mason University, June 2008. Advisor: K. E. Wage. [published]

Richard Wheelock, *Measurement of Angular Spread of Signals in SWellEx-96 Using Multitaper Array Processing*, Master's thesis, George Mason University, August 2008. Advisor: K. E. Wage. [published]

T. K. Chandrayadula and K. E. Wage, "Interpolation methods for vertical linear array element localization", *Proceedings of the 2008 IEEE/MTS Oceans Conference*, to appear, September 2008. [in press]

HONORS/AWARDS/PRIZES

Professor Kathleen E. Wage will receive the Mac E. Van Valkenburg Early Career Teaching Award from the IEEE Education Society at the Frontiers in Education Conference in October 2008.

Kathleen Wage received tenure and was promoted to Associate Professor of Electrical and Computer Engineering at George Mason University in 2006.